Experience with EHV Transmission Up to 765kV

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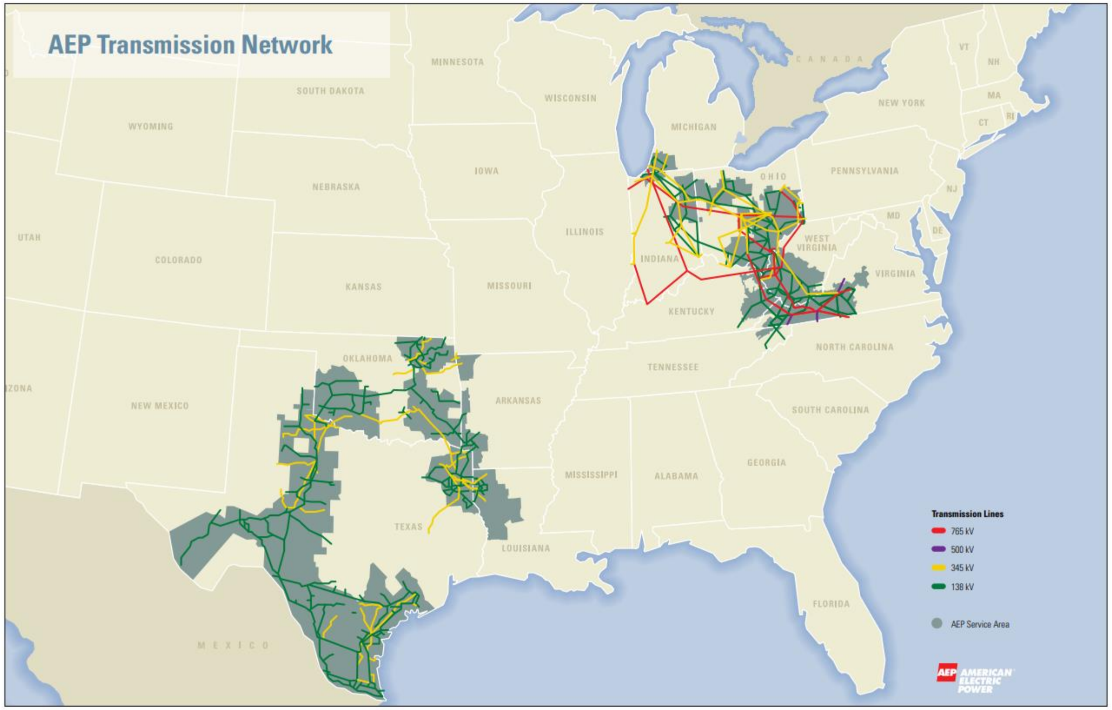
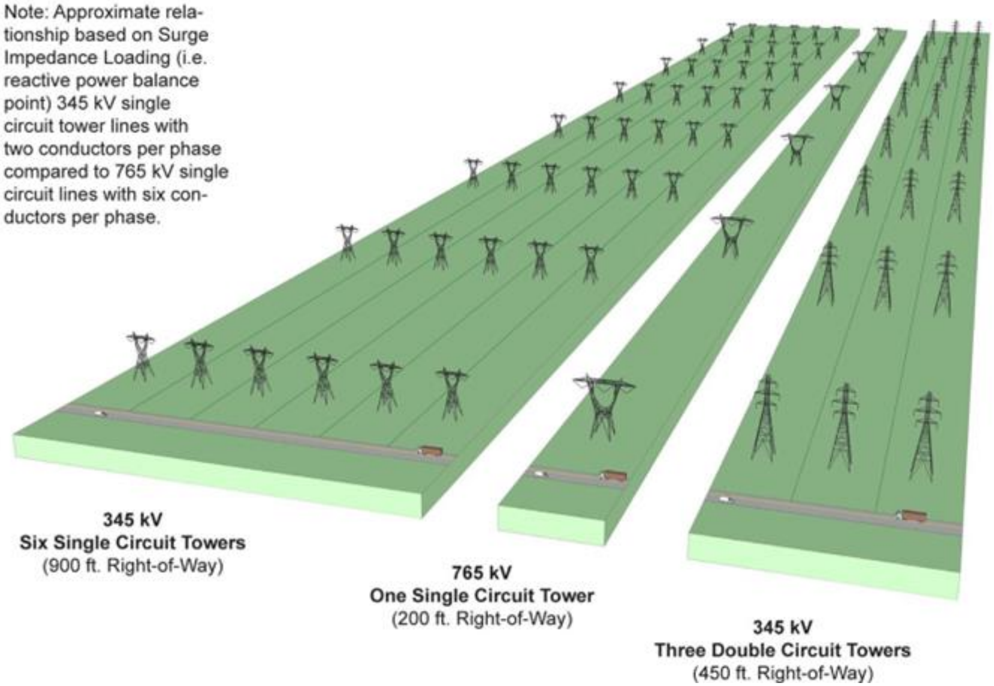
About AEP

- 5.5 million customers over 11 states.
- Over 8,000 miles of EHV transmission, across 3 RTOs including 2,200 miles of 765kV.
- 30,000 MW of generating capacity.



Experience with 700+kV

- **700+kV systems have been operating in North America since the 1960's.**
  - Primarily AEP and Hydro Quebec.
- **Other facilities up to 1000kV are being used in South Korea, China, Japan, Russia, South Africa, Venezuela, Brazil, and India.**
- **Higher voltages used to provide:**
  - Higher capacity.
  - Lower impedance, allowing for transfers over longer distances.
  - Lower energy losses.
  - Economies of scale – lower cost per MW, more MW in less ROW.


Note: Approximate relationship based on Surge Impedance Loading (i.e. reactive power balance point) 345 kV single circuit tower lines with two conductors per phase compared to 765 kV single circuit lines with six conductors per phase.

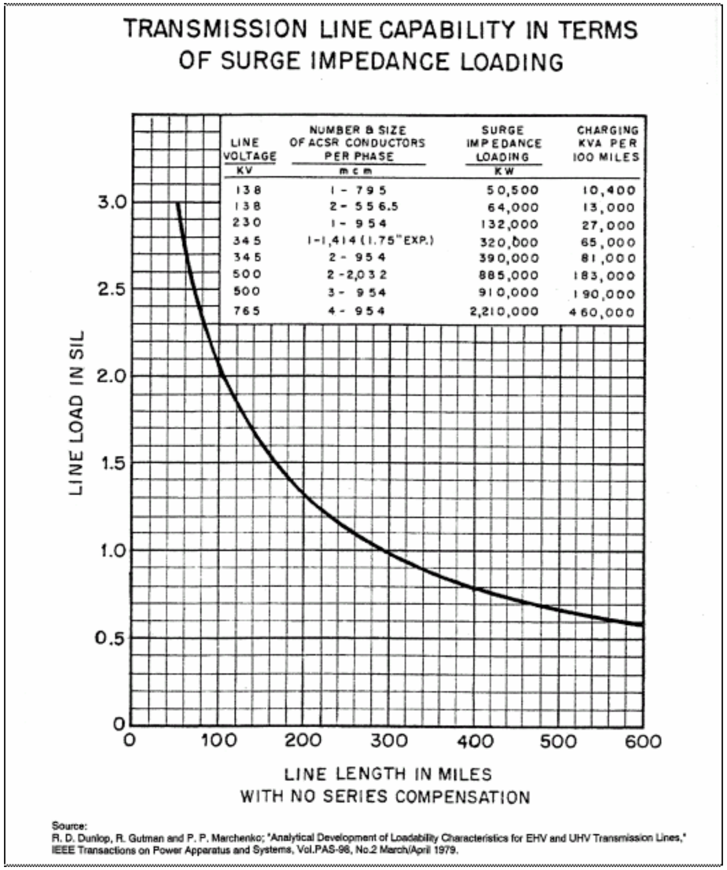
345 kV
Six Single Circuit Towers
(900 ft. Right-of-Way)

765 kV
One Single Circuit Tower
(200 ft. Right-of-Way)

345 kV
Three Double Circuit Towers
(450 ft. Right-of-Way)

Capacity vs. Loadability

- **Thermal capacity is based on the physical characteristics (i.e., the conductor type and size).**
  - Shorter lines typically limited by thermal capacity.
- **Actual loadability, which varies based on line length, must also consider reactive power consumption.**
  - Voltage and stability limit loadability.
- **Loadability is influenced by:**
  - Voltage level.
  - Structure geometry.
  - Conductor/bundle.
  - External reactive compensation.



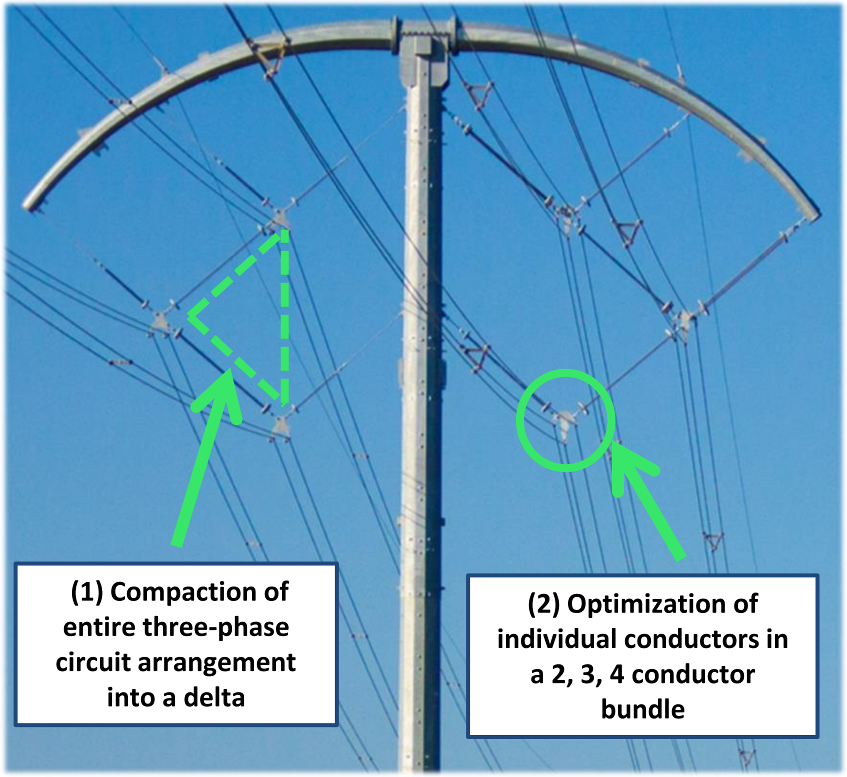
TRANSMISSION LINE CAPABILITY IN TERMS OF SURGE IMPEDANCE LOADING

LINE VOLTAGE KV	NUMBER & SIZE OF ACSR CONDUCTORS PER PHASE mcm	SURGE IMPEDANCE LOADING KW	CHARGING KVA PER 100 MILES
138	1 - 795	50,500	10,400
138	2 - 556.5	64,000	13,000
230	1 - 954	132,000	27,000
345	1-1,414 (1.75" EXP.)	320,000	65,000
345	2 - 954	390,000	81,000
500	2 - 2,032	885,000	183,000
500	3 - 954	910,000	190,000
765	4 - 954	2,210,000	460,000

Source:
R. D. Dunlop, R. Gutman and P. P. Marchenko; "Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines," IEEE Transactions on Power Apparatus and Systems, Vol.PAS-98, No.2 March/April 1979.

How BOLD Works

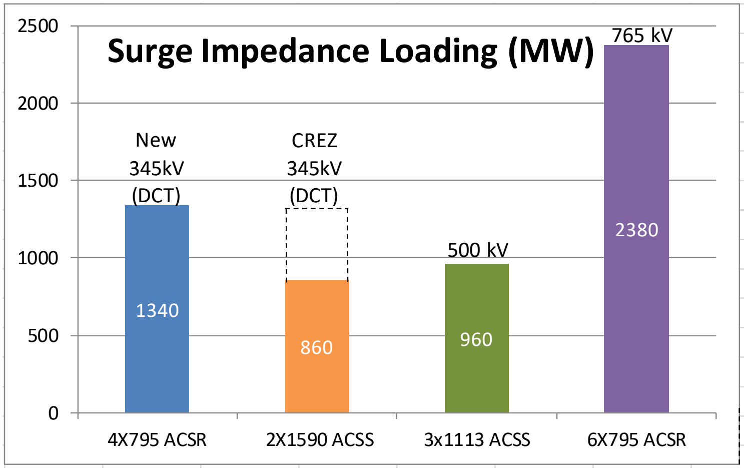
- **Leverage physics to maximize electrical performance:**
  (1) Reduce phase separation into a "delta" configuration.
  (2) Optimize conductor size and bundle diameter.
- **Reduces line inductance (L) and increases capacitance (C)**
  - **Overall impedance (Z) is reduced**
- **Higher degree of intrinsic "self-compensation".**

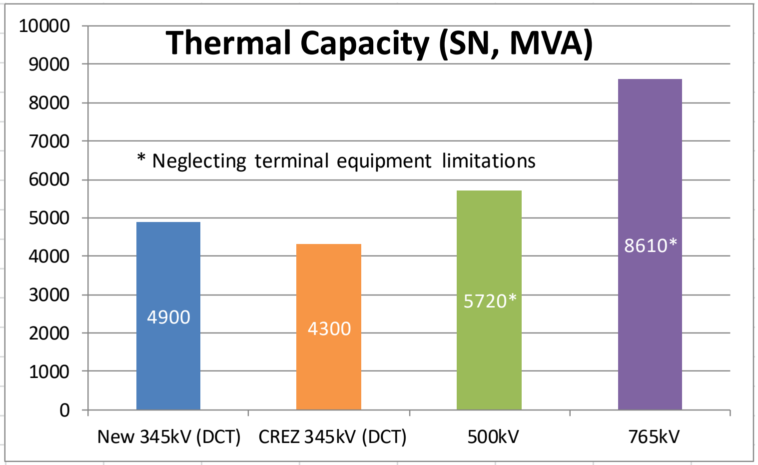


(1) Compaction of entire three-phase circuit arrangement into a delta

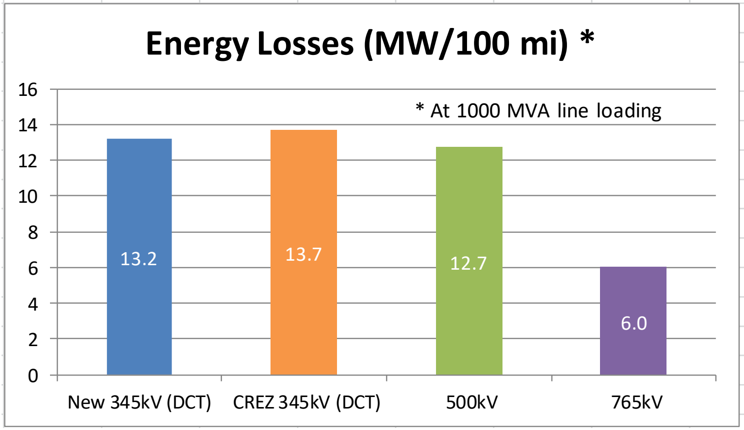
(2) Optimization of individual conductors in a 2, 3, 4 conductor bundle

Comparison of HVAC Lines

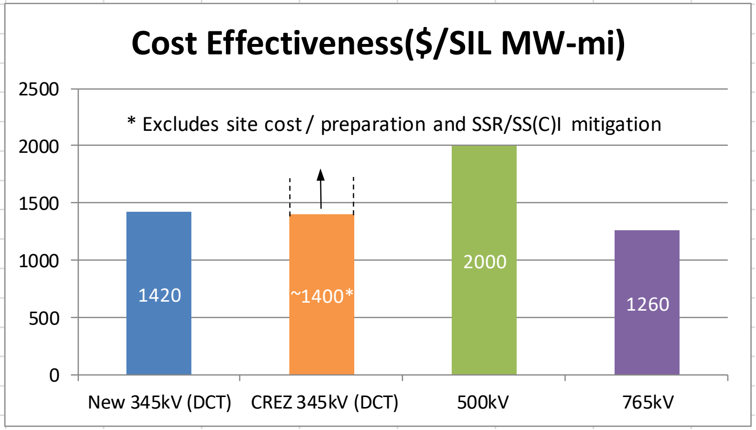

Surge Impedance Loading (MW)


Thermal Capacity (SN, MVA)

* Neglecting terminal equipment limitations


Energy Losses (MW/100 mi) *

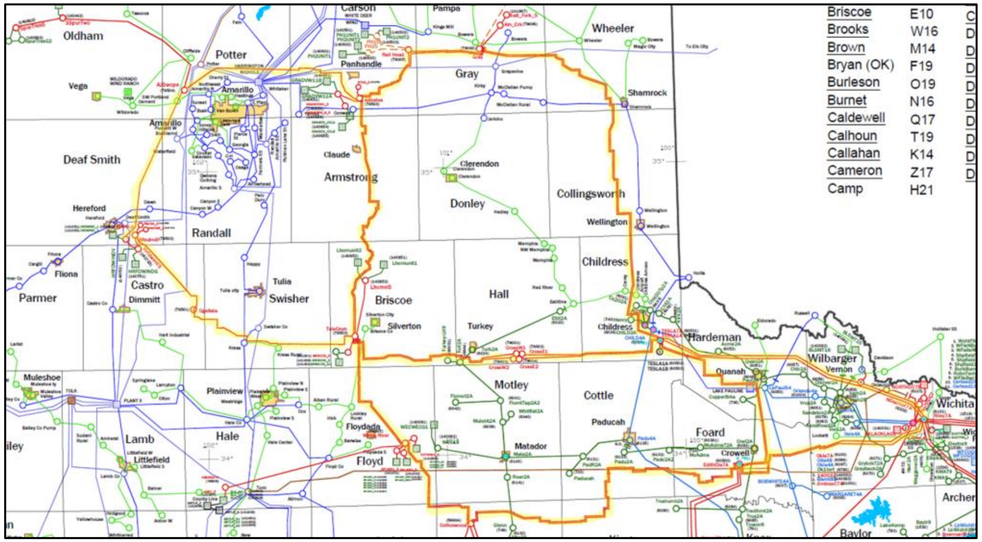
* At 1000 MVA line loading


Cost Effectiveness($/SIL MW-mi)

* Excludes site cost / preparation and SSR/SS(C)I mitigation

West Texas Case Study

- Generic Transmission Constraints (GTCs) in ERCOT based on stability limits.
- Reactive limits on 345kV CREZ facilities today managed with series capacitors.
- BOLD design analyzed in comparison to existing system to demonstrate the impact of lowering line impedance.



West Texas Case Study

Table 1 – Contingency simulation results

Contingency	80% (6206.26 MW)			85% (6594.15 MW)			90% (6982.04 MW)			95% (7369.93 MW)			100% (7757.82 MW)		
	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2
Event 1	Stable	Stable	Stable	Marginally stable[1]	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Marginally stable[2]	Marginally stable[5]
Event 2	Stable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Marginally stable[3]	Stable
Event 3	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable
Event 4	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable
Event 5	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Stable	Unstable	Marginally stable[4]	Marginally stable[6]
Event 6	Stable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Stable	Unstable	Stable	Unstable

- Case 0 is the base case(DWG 2023HWLL). By default, one Gauss series capacitor is bypassed. The rest (two at Cross, two at Kirchhoff, one at Gauss) are in service.
- Case1 is Case 0 + BOLD substitutions
- Case2 is Case 1 + two series caps at Cross bypassed

With series capacitors in service, BOLD technology could increase 1,103MW transfer capability (from 80% to 95%) while maintaining stability.

West Texas Case Study

Table 2 – Contingency simulation results-without series capacitor

Contingency	65% (5042.58 MW)		70%(5430.47 MW)		75% (5818.37 MW)		80% (6206.26 MW)		85% (6594.15 MW)		90% (6982.04 MW)		95% (7369.93 MW)		100% (7757.82 MW)	
	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4	Case 3	Case 4
Event 1	Stable	Stable	Stable	Stable	Stable	Stable	Marginally stable	Stable	Marginally stable[a]	Stable	Unstable	Stable	Unstable	Unstable	Unstable	Unstable
Event 2	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Unstable
Event 3	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Marginally stable[b]
Event 4	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Marginally stable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Marginally stable[c]
Event 5	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Unstable
Event 6	Stable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Unstable	Unstable	Unstable	Unstable

- Case3 is Case 0 + series caps at Cross, Gauss and Kirchhoff bypassed
- Case4 is Case 3 + BOLD substitutions

Without series capacitors, BOLD technology could increase 1,940 MW transfer capability (from 65% to 90%) while maintaining stability.

Solution Considerations

- **Region/system-level design.**
  - Line-by-line comparisons may not demonstrate full value of different technologies.
- **Voltage control needs.**
  - Reactors.
  - Capacitors.
  - FACTS Devices.
- **Interconnections.**
  - Current/future development.
- **SSO/SSCI interactions.**
- **Long-term maintenance.**
- **Overall cost and benefits.**

Conclusions

- Long-distance transmission is not just about a capacity, but system stability.
- Higher-voltage transmission, up to and including 765kV, has been used as an efficient and cost-effective means to bridge long distances for decades.
- Different technologies can complement one another to provide maximum value to the system.
- Solutions should consider a long-term overall system view (HVDC, 765kV, 345kV, FACTS or a combination).